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The design, construction and in-service performance of the all-composite Aberfeldy footbridge

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INTRODUCTION

The world's longest span advanced composite bridge was opened on 3rd October 1992. It crosses the River Tay in Scotland, where it connects the two halves of Aberfeldy golf course. The bridge combines a variety of innovative advanced composite technologies, including a pultruded glass-fibre-reinforced-polymer (GFRP) deck and aramid cables.[1] The bridge was fabricated on site with minimal heavy equipment, causing significantly less disruption than a conventional steel or concrete structure, and offered a cost-effective solution to the golf club.[2]

This paper reviews the design, construction and in-service performance of the bridge, as we approach the tenth anniversary of its construction.

DESIGN

The Aberfeldy bridge is a symmetrical cable stayed footbridge, with A-frame towers (Figure 1). The deck has an overall width of 2.12 m, and a total length of 113m, made up of a 63m main span over the river, a two back spans of 25m. The deck is stiffened by 4 fans of 5 cables, anchored to the ground via short aluminium columns under the back spans. Figure 2 shows the bridge in elevation, and indicates the composite materials used in its construction.

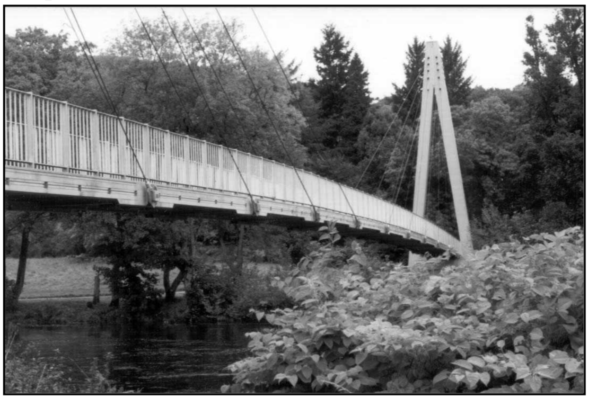

Figure 1: The Aberfeldy bridge (October 2000)

The bridge contains 14.5 tonnes of composite material. The GFRP deck, towers and parapets account for the majority of the composite in the structure. These are combined with aramid stay cables.

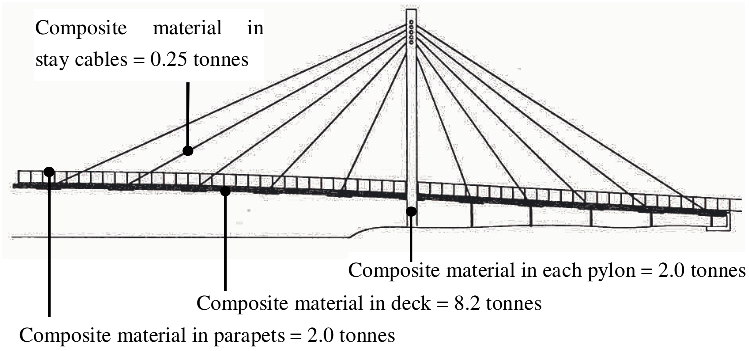

Figure 2: Elevation of the bridge, showing material quantities.

Design loads

The bridge was designed to carry live loading of 5.6kN/m (3.52kN/m^2) in accordance with UK Highways Agency Departmental Standard BD 37/88. The dead weight of the bridge is significantly less, at only 2.0 kN/m including 1.0kN/m ballast. Wind and temperature design loads were also to BD37/88.

Design criteria for dynamic behaviour

Due to the bridge's high live to dead load ratio and slender proportions control of dynamic effects was a critical design issue. To this end, ballast in the form of concrete filling of the cells of the central deck panel was specified. Its purpose was to prevent uplift under wind, improve the transverse mass distribution of the deck, improve safety against flutter instability, and improve footfall behaviour. The bridge was designed to meet the aerodynamic stability rules subsequently incorporated in BD 49/93. Given the intended use of the bridge in a private golf course, the bridge was not designed to comply with the allowable footfall response specified in BD 37/88.

Deck and towers

The deck and towers of the bridge were wholly fabricated from the Advanced Composite Construction System (ACCS). This comprises a small number of modular component types which are pultruded from E-glass fibre and isophthalic polyester resin and are connectable by a combination of bonding and toggle type mechanical connectors.

A Limit-State design methodology was used, with factors of safety based on previous Reliability theory based development work. The thin-walled composite components are generally governed by allowable strain at the Serviceability Limit State, or buckling at the Ultimate Limit State. Critical buckling modes include both global buckling and local buckling of the walls of the sections.

The components were joined using a combination of bonding and mechanical interlock (Figure 3). Over 2km of mechanical toggles were used, which draw the

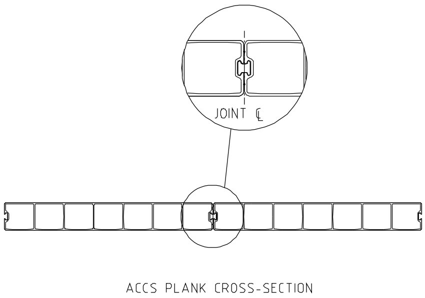

Figure 3: Interlock of ACCS components.

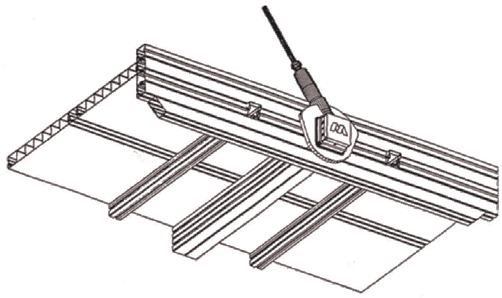
Figure 4: The arrangement of the bridge deck.[6]

bonding surfaces together to a predetermined bondline thickness, to give a high quality joint that can be readily and accurately assembled under site conditions.

Figure 4 shows the structural form of the bridge deck. The deck is formed by 600 mm wide longitudinal panels and is stiffened by edge beams and cross beams formed from 80 x 80 mm '3-way connector' components. Primary cross beams are provided at 5.73 m intervals at cable anchorage locations, and secondary cross beams at 955 mm intervals. A rubber surfacing membrane (formerly a conveyor belt) protects the deck.

Parapets
The parapets were constructed from non-ACCS pultruded GFRP sections. The parapet posts pass through holes in the bridge deck, and are anchored to the deck by a combination of a bonded boundary angle above the deck and dowels below the deck. Top and bottom rails span between the posts, with closely-spaced CHS vertical members between the rails. Dundee University performed load tests to verify the strength of the parapets.

Cables
The bridge deck is supported by Parafil rope stays. These lightweight cables comprise a core of parallel Kevlar-49 fibres, sheathed in low density polyethylene.

Details at the end of the cables (where high stress concentrations occur) were fabricated from conventional construction materials. The cable terminations and the deck connections are in aluminium, while the tower connections are in galvanised steel. Testing was undertaken by Dundee University to check the strength of these connections.

Foundations
An important advantage of lightweight composite construction is that the Aberfeldy bridge could be founded on simple pad footings. The main criterion dictating the size of the foundations was the weight required to resist uplift, rather than the contact area to control settlement.

CONSTRUCTION

Fabrication and erection was carried out by a small team of students from Dundee University (with support from the consultant and an engineering management contractor), and took just 8 weeks. No expensive construction plant or major temporary works were required, with minimal disruption and no damage to the golf course.

Fabrication

The tower legs were fabricated by bonding under factory conditions off-site. The deck, on the other hand, was supplied to site in its component parts, and fabricated on one side of the river on the axis of the bridge. Fabrication was carried out under cover of a tented structure, which protected the deck from the elements during the 24 hours required for the adhesive to cure.

Erection

The method of erection used for the Aberfeldy bridge is unique amongst cable-stayed structures, and was rendered possible by the use of lightweight materials.[3]

The tower legs were assembled on the ground and hinged to their concrete footings. They were then raised using an all-terrain forklift to an angle of about 30° above the horizontal, whence they were lifted to the vertical position by means of simple Tirfor hand winches, and held in position by guy ropes (Figure 5). The cable stays and primary cross-beams were then installed, and a temporary cable net created to hold the cross beams in position across the river. The cross-beam and cable net formed a framework over which the deck could be pulled into position by incremental launching, using a winch on the far side of the river.

Figure 5: Erection of the North Tower.

DECK STRENGTHENING FOR INCREASED LOADINGS

The bridge was overloaded when it was crossed by a small tractor towing a trailer of sand. As a result of the high concentrated wheel loads, cracks formed in the top surface of the GFRP deck, parallel to the webs of the cellular sections.

To remedy the situation, the deck was strengthened during the spring of 1997. GFRP pultruded plates were bonded to the top of the deck (beneath the rubber

Figure 6: CFRP strengthening of the edge beam

surfacing), with rivets providing fixity while the adhesive cured. At the same time, CFRP pre-preg sheets were applied to the deck edge beams on either side of the primary transverse beams, to handle the increased cable reactions (Figure 6). The strengthening added some 0.17 kN/m to the weight of the structure.

IN-SERVICE PERFORMANCE

Because of its innovative character, the in-service behaviour Aberfeldy Bridge has received considerable interest. A team led by Bill Harvey, then of the University of Dundee, undertook a monitoring programme immediately following the opening of the bridge. At later stages two other research teams carried out field tests to determine the bridge's dynamic performance. The bridge has also received a number of condition surveys.

Dynamic performance

Two experimental investigations into the dynamics of structures under footfall loading have been conducted on the bridge, in 1995[4] and 2000.[5] The latter investigation was prompted by recent experience with the Millennium bridge in London, and investigated the possibility of lock-in of pedestrian loading with the lateral vibration of the bridge. (The results showed that lock-in could occur, but were inconclusive).

Details of the first few natural modes of vibration determined by these studies are shown in Figure 7, and listed in Table 1. The damping ratio is referred to the critical damping level.

During the tests conducted in 1995,[4] a peak acceleration of 0.22g was measured when a person deliberately walked with a pace coinciding with the first fundamental natural frequency of the bridge. This acceleration is considerably higher than the maximum acceleration criterion in BD37/88.

Between the two investigations the deck was strengthened to cater for the increased loading from golf buggies. As a result of the bonding of GFRP plates to the upper surface of the deck[5], the mass of the deck, and the stiffness of the deck (in particular, the lateral stiffness) were increased. As a consequence, the natural frequencies measured during the tests in 2000 were marginally lower, and the dynamic stability of the bridge improved.

Mode*	Frequency (Hz)		Damping ratio for empty structure (%)	
	1995	2000	1995	2000
H1	1.00	0.98	-	1.0
V1	1.59	1.52	0.84	0.4
V2	1.92	1.86	0.94	0.7
V3	2.59	2.49	1.20	0.7
H2	2.81	2.73	-	1.2
V4	3.14	3.01	-	0.8
T1	3.44	3.48	-	5.5
V5	3.63	3.50	-	0.6
V6	4.00	3.91	-	0.9
T2	4.31	4.29	-	3.2
V7	4.60	4.40	-	0.8
V8	5.10	4.93	-	1.8

* H = horizontal, V = vertical, T = torsional

Table 1: Dynamic response of Aberfeldy bridge, from studies in 1995,[4] and 2000.[5]

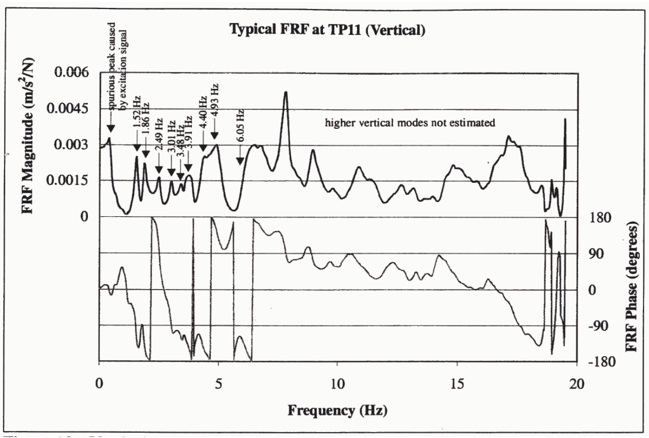

Figure 7: The frequency response of Aberfeldy bridge, from the 2000 study.[5]

The design of the bridge ensured that the first torsional and vertical natural frequencies are well separated, to maximise the critical wind speed for aerodynamic flutter. This was achieved by incorporating ballast along the centre line of the bridge.

The damping ratios measured at Aberfeldy (Table 1) are not significantly different to the value of 0.75% determined for the deck in isolation during a LINK research programme into the ACCS system (with the exception of the low damping ratio for the first vertical mode suggested by the study in 2000). This suggests that the other bridge components, principally cables, parapets, and surfacing, do not make a significant contribution to damping. The parallel-lay aramid fibres in the cables dissipate far less energy than spiral-wound cables, and the thin rubber surfacing contributes little to damping. Although the parapets were fitted with frictional sliding joints to improve damping, these do not appear to have been effective, due to looseness in the sliding joints and in the connections between the parapet posts and the deck. Pavic *et al.*[5] noted that the damping increased with the number of people on the bridge.

Weathering

Within its first year of service, the structure withstood hurricane force winds, unprecedented snowfall, and flooding to above deck level in the back spans.[6] These moderately extreme adverse conditions did not cause damage, and the primary structure of the bridge continues to perform very well.

However, from a surface weathering point of view, some details have fared less well, although in no case has weathering adversely affected the overall structural safety of the bridge.

Superficial weathering effects

There has been considerable erosion of the resin-rich surface layer of the parapet components, in some instances exposing the fibres. The parapets were fabricated from non-ACCS GFRP sections, which were pultruded to a different specification from the ACCS components in the primary bridge structure. These were the only suitable sections available within the cost and time constraints at the time. This shows how important the detailed specification of resin and manufacture of these materials is in practice. The worst affected areas are the upper surface of the handrails and the lower region of the posts. The handrail erosion is likely to be the combined effect of environmental weathering and abrasion, since resin loss is less widespread on the lower rail. The handrail is inevitably subjected to a large amount of wear, both due to its normal function, and to people who climb over the parapet to jump into the river below. Another region where surface resin loss has been observed is at the base of the posts, many of which are badly scuffed.

There is very little loss of surface resin over the remainder of the structure. The ACCS components incorporate a protective surface veil that guarantees a resin rich surface of constant thickness. One exception, however, is a substandard ACCS panel that was used as a plaque, which has suffered significant resin loss, and delamination cracking. This panel is not subjected to any load, and thus degradation is purely driven by the environment.

Performance of the parapets

Flexing of the deck is accompanied by movement of the parapets (Figure 7). This was recognised during design, and the parapet rails were connected to posts using sleeved connection to a FRP plate pinned to the posts so as to allow some relative movement. However, the connections have generally worked loose, and in some cases the rails no longer remain in their sockets. Furthermore, many of the post to deck connections are loose. These effects are the result of movement cycles of the deck and could be avoided by giving the parapet connections greater movement capacity or by reducing deck displacements by means of a stiffer cable system.

In some cases, the parapet posts have suffered impact damage near their base, leading to delamination. Golf buggy use was not envisaged in the original design, and the parapet was not designed for impact. Thus, damage would also have occurred even if the posts had been made from conventional materials. Such damage could be mitigated by the addition of protective kick-boards at the base of the railings.

Mould growth
Both the parapets and the primary structure have been affected by mould and moss growth, especially on north-facing surfaces and in the gutter areas where due to lack of maintenance free drainage is impeded and water is trapped (Figure 7). This is due in part to standing surface moisture retained by dirt and debris, and in part by moisture absorption of the composite, which, in contrast to the aluminium components, which are free from mould, absorbs up to 1.5% by weight of moisture. Similar effects can be observed on traditional masonry structures in the area, due to the damp climate. The mould growth observed has little impact on structural strength, however, being primarily a maintenance and aesthetic issue. Due to the modular construction system, the edge beam inevitably contains grooves and indentations, and these also act as moisture traps, providing a foothold for minor mould growth.

A strategy towards managing mould growth under similar exposure conditions might include selection of appropriate colours for the composites to minimise the visual impact of mould growth, the use of mould-inhibiting additives in the resin system, detailing to avoid water traps, and a maintenance regime to ensure that drainage paths are kept clear of leaves and other debris.

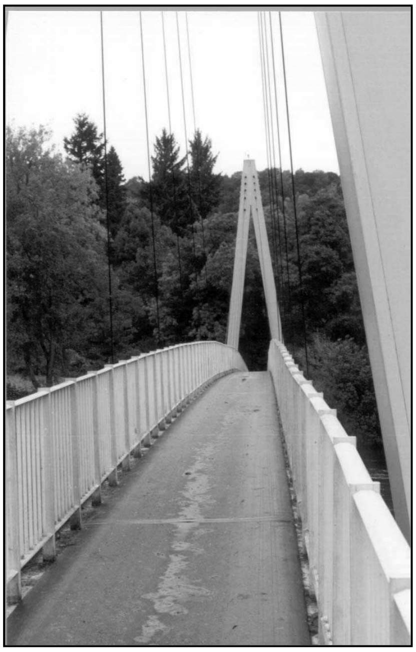

Figure 8: Looking north along the bridge, October 2000.

CONCLUSIONS
The primary structure of the advanced composite Aberfeldy bridge has proved very successful in demonstrating the feasibility of advanced composite materials for

constructing long span bridge structures cost-effectively. It has been readily strengthened to cater for additional loading imposed by golf buggies by the addition of carbon fibre composite to the upper surface of the deck. The dynamic behaviour of the bridge is relatively lively, on account of its ultra-lightweight construction and its below expected damping value, but the dynamic response is considered acceptable for the bridge's intended use. Studies have demonstrated that the dynamic response can be readily controlled by calibrating the magnitude and distribution of the mass of the deck, and tailoring the damping of the parapets, cables, and surfacing.

The GFRP parapets have proved less durable than the primary structure, due to movement of the joints associated with flexing of the deck and the different specification of the parapet components. The surface resin has been eroded from the top handrail (exposing the glass fibres), and some of the posts have suffered impact damage from golf buggies. Both these problems can be readily mitigated.

The structural use of advanced composite materials continues to grow, and systems are now available which are capable of carrying full highway loading.[7] Ten years after its construction, the Aberfeldy footbridge remains an innovative demonstration of the structural use of composites, and continues to attract world-wide attention.

REFERENCES:

1 Harvey W.J., "A reinforced plastic footbridge, Aberfeldy, UK", Structural Engineering International, 4/93, pp. 229-232

2 Lee D.J. (1993) "Project Linksleader: The first major cable-stayed GRP bridge." FIP symposium, "Modern prestressing techniques and their applications" Kyoto, Japan: FIP. Vol.2 pp. 671-678

3 Burgoyne C.J., Head P.R., "Aberfeldy bridge – an advanced textile reinforced footbridge", TechTextil symposium, Frankfurt, Germany, June 1993.

4 Pimentel R.L., Waldron P., Harvey W.J., "Assessment of the dynamic behaviour of Aberfeldy GRP plastic cable-stayed footbridge", Seminar on Analysis and Testing of Bridges, pp. 38-40, Institution of Structural Engineers, London, April 1995.

5 Pavic A., Reynolds P., Cooper P., Harvey W.J., "Dynamic testing and analysis of Aberfeldy footbridge", Final report, Ref. CCC/00/79A, The University of Sheffield, Department of Civil and Structural Engineering, Vibration Engineering Section, 31 July 2000.

6 Head P.R. "Cost effective advanced composite structures designed for life in the infrastructure", BPF congress, 1994.

7 Daly A.F. "Developments in modular FRP decking for highway bridges", Bridges 2001, Aston University, Oct 2001.